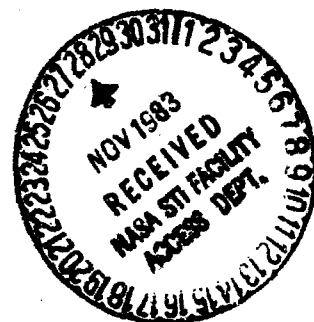


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# A Review of the Use of Wear-Resistant Coatings in the Cutting-Tool Industry



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(NASA-TM-83512) A REVIEW OF THE USE OF  
WEAR-RESISTANT COATINGS IN THE CUTTING-TOOL  
INDUSTRY (NASA) 11 p HC A02/MF A01 CSCL 11C

N84-11295

Unclas  
G3/27 42458

Presented at the  
International Workshop on Industrial Applications of Plasma Chemistry  
sponsored by the Israeli Research Council  
Ashkelon, Israel, April 1981

**NASA**

A REVIEW OF  
THE USE OF WEAR-RESISTANT COATINGS IN THE CUTTING-TOOL INDUSTRY\*

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SUMMARY

The main mechanisms involved in the wear of cutting tools are reviewed and applied for the evaluation of the different coating properties required for the reduction of the different kinds of wear. The types of coatings commonly used today in the cutting-tool industry, their effect on tool life and their ranges of applicability are presented and discussed in view of their properties. Various coating processes as well as their advantages and shortcomings are described. Potential future developments in the field of wear-resistant coatings are discussed.

INTRODUCTION

Cutting tools have to satisfy different requirements regarding the bulk and the surface. The bulk has to be tough in order to prevent the propagation of cracks which are formed mainly at the surface and also has to be hard in order to resist plastic deformation. The main requirement from the surface, which is our main concern here, is resistance to wear. These requirements are hard to meet using one kind of material and this has led to the development of coated tools in which the surface material is different from that of the bulk.

The first industrial usage of coatings in the cutting-tool industry was inspired by a work done at the Laboratoire Suisse de Recherches Horloges (ref. 1) where a CVD process for coating moving parts with titanium carbide was developed with the purpose of reducing their wear rate, and the first patent for coating cemented carbide cutting tools with TiC was filed in 1969 by Sandvik (ref. 2). Since then the use of coated cemented carbide cutting tools has grown constantly and today some 50 percent of cemented carbide cutting tools are coated.

The purpose of this paper is to present and discuss the main considerations involved in selecting the coating materials and the coating process as well as their advantages, shortcomings, and range of applications.

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\*Material previously presented at the International Workshop on Industrial Applications of Plasma Chemistry, Ashkelon, Israel, April 1981.

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## MECHANISMS OF WEAR IN CUTTING TOOLS

In order to determine the factors affecting the performance of wear resistant coatings, it is necessary to know the main mechanisms which are responsible for the wear of cutting tools. An excellent survey of this subject has been given by Trent (ref. 3) and here a brief review of the various mechanisms will be presented. These can be divided into the following categories:

(1) Adhesive wear. When two clean surfaces are in contact with each other, a bond is formed between them. This phenomenon is also termed often "cold welding." Experimental and theoretical studies performed by Buckley (ref. 4) and Ferrante (ref. 5) have shown that in the case of two metallic materials the interface is stronger than the weaker of the two materials but weaker than the stronger of two materials and thus when the two surfaces are parted there is a transfer of the weaker material to the surface of the stronger material, i.e., wear of the part made of the weaker material occurs.

(2) Abrasive wear. This type of wear occurs when a hard, rough surface slides against a softer surface, digs into it and plows grooves in it. The material originally in the grooves is normally removed in the form of loose fragments. This type of abrasive wear is called two-body abrasive wear (ref. 6). Another type of abrasive wear occurs when hard particles are present between the sliding surfaces and abrade material off each. The mechanism in this case seems to be that an abrasive grain adheres to one of the surfaces, or else is embedded in it, and plows out a groove in the other (ref. 7). This type of abrasive wear is termed three-body abrasive wear. In metal cutting this type of wear occurs when the work materials contain particles of phases which are harder than the tool. For example, in cast iron and also in steel there are particles of carbides and oxides which are harder than the carbides used as the basis for cemented carbides, i.e., WC, TiC, and TaC, and these abrade the cutting tool.

(3) Corrosive wear. This kind of wear is caused by chemical reaction with the environment. In the case of a friction system the danger of corrosive damage is much more severe than in the usual case since the contact between the surfaces brings about disruption of protective surface layers which are formed in many cases and contribute to the corrosion resistance. Thus, fresh surfaces having an inferior corrosion resistance are continuously exposed.

(4) Diffusional wear. This type of wear takes place at high temperatures. At these temperatures, diffusion of certain components, mainly carbon, from one part to the other occurs. This weakens the material thus causing fracture of fragments.

When examining worn cutting tools one can observe two regions of wear as shown in figure 1. Wear occurring at the clearance face is termed flank wear and wear occurring at the rake face is termed crater wear. Flank wear is usually due to irregular flow of the work material past the cutting edge, causing tearing of fragments off the tool surface. This mechanism which is called attrition wear is prominent at low cutting speeds. As for the crater wear, studies conducted by Trent (ref. 8) and by Lolazde (ref. 9) show that the mechanism involved there is diffusional wear. During metal cutting the highest temperature is attained on the rake face at a distance of approximately 1.5 mm from the edge (ref. 14) reaching 1000° C or more.

At these high temperatures carbon has an appreciable solubility in steel and since the diffusion coefficient also increases sharply with temperature, diffusion of carbon from the tool to the chip takes place thus causing weakening of the latter and resulting in crater wear.

## PROPERTIES OF COATING MATERIALS

We are now in a position to assess the desirable properties of the coatings. These are:

(1) Hardness. According to the classical work of Khrushchov and Babichov (ref. 10), the abrasion resistance is proportional to hardness. Thus, it is clear that the coating material has to be as hard as possible in order to minimize this severe form of wear. The hardest materials found in nature are diamond having a hardness of 80 GPa and cubic boron nitride having a hardness of 45 GPa. It might have therefore been concluded that diamond would be the ideal coating material. This, however, is not universally true. Diamond tools are produced by some manufacturers and it is found that they have a very high wear rate when machining ferrous alloys. This proves that a wear mechanism other than abrasion is involved in this case. This problem is not encountered when machining ferrous alloys with cubic boron nitride. However, like diamond, it is thermodynamically unstable and no industrial technique for its deposition as a coating has yet been developed.

(2) Adhesion. This is a very important factor since in many cases failure of coated inserts results from peeling of the coating. The factors which affect adhesion, especially between metallic and nonmetallic materials are not yet well understood. For a long time it was believed that the best adhesion is obtained when the substrate surface is clean. This is true in many cases where contaminants prevent the formation of a bond between coating and substrate. On the other hand, in other cases, like the cases of Al, Cr, and Fe on glass substrates which were the subject of the classical work of Benjamin and Weaver (ref. 11), exposure of the glass surface to oxygen enhances adhesion. This was attributed to the formation of an oxide having a stronger bond than the metal-glass bond at the interface. The development in recent years of surface analytical tools (AES, ESCA, etc.) made it possible to examine this hypothesis and studies performed by Pepper (ref. 12) show that exposure of the surface to very small amounts of oxygen (less than a monolayer) which does not form any chemical bond with the metal enhances the adhesion significantly. On the other hand, exposure to  $\text{Cl}_2$  reduces adhesion.

(3) Corrosion resistance. Since most coating materials are stable non-metallic compounds, no serious corrosion problem exists and, in fact, the coating improves corrosion resistance.

(4) Resistance to diffusion. This property is important mainly at high temperatures. Since the temperatures encountered in metal cutting are of the order of  $1000^\circ\text{C}$  or higher (ref. 13) where appreciable diffusion takes place it is of great importance there.

Once this was understood it was rather obvious that one way of reducing crater wear is the application of a diffusion barrier. The material which was first picked up for this purpose was TiN which was applied on top of the TiC coating with an intermediate layer of TiCN for matching purposes. This reduced crater wear by some 50 percent as can be seen in the machining test results presented in figures 2 and 3. TiN has another very important characteristic, namely its golden color. This fact was not ignored by the advertising departments of many manufacturers.

The next development in the field was the introduction of an even better diffusion barrier -  $\text{Al}_2\text{O}_3$ , which in addition is harder than TiN.

(5) Thermal Properties. Because of the high temperatures attained at the work/tool interface it is intuitively at least clear that the thermal properties of the tool surface play a substantial role in its wear behavior.

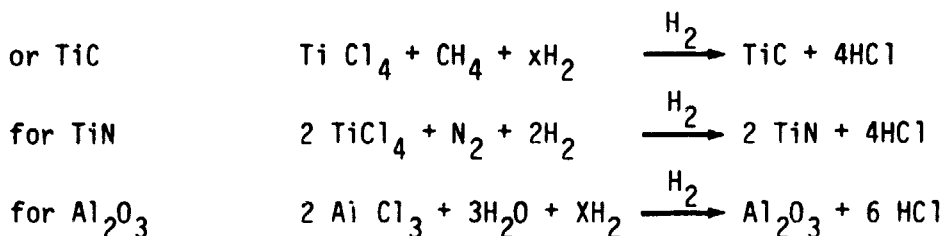
Experimental data (ref. 15) indicate that tools with lower thermal conductivity have a shorter tool-chip contact length and lower wear rate in both clearance and rake face. This was explained by Lenz, et al. (ref. 16) in terms of transient heat conduction considerations.

Figure 4 shows the heat conductivity of some wear-resistant materials. One can see that the thermal conductivities of both TiC and TiN increase with temperature, that of TiN being substantially lower than that of TiC. The heat conductivity of  $Al_2O_3$ , however, behaves in the opposite manner, i.e., decreases with temperature. This is reflected in the wear behavior of tools coated with this material - whereas at low cutting speeds there is no big difference between the wear rates of tools coated with TiN and those coated with  $Al_2O_3$ , there is an improvement in wear rate at high cutting speeds as can be seen in figure 5.

Another thermal property of importance is the melting temperature and even more so the softening temperature defined as  $0.47 T_m$  where  $T_m$  is the absolute melting temperature. The values of these parameters for the three most common wear-resistant materials are given in table I. Other thermal properties of the coating materials like the coefficient of thermal expansion and thermal shock resistance, also affect the wear behavior, but have not as yet been studied.

#### COATING PROCESSES

The most common industrial process by which wear-resistant coatings are applied in chemical vapor deposition (CVD). The reactions are:



All these processes require temperatures around  $1000^\circ C$ . These high temperatures affect the substrate as reflected by the lower transverse rupture strength (TRS) of coated cemented carbides as compared with uncoated ones.

Recently some Japanese manufacturers claimed they were using reactive ion plating for the coating of milling grades which require a high TRS. The process is sketched in figure 6. It is done in a reactive gas atmosphere and consists of evaporation (usually by means of electron beam) of the desirable metal (titanium or aluminum) and ionization of a fraction of the reactive gas molecules by means of electric field. This induces chemical reaction between the evaporated metal and the reactive gas and results in formation of a compound coating. No details of the process as well as of the performance of the coated tools were given.

#### FUTURE DEVELOPMENTS

The main R and D effort is currently directed towards finding methods of low-temperature deposition of coatings. Such methods will enable application of protective coatings which is limited at the present to cemented carbides,

to high-speed tools as well. The methods which are explored are reactive ion plating, sputtering and plasma-assisted chemical vapor deposition (ref. 17) where the reacting species are excited by means of plasma rather than by high temperature and organometallic chemical vapor desposition.

Introduction of new coating materials is not to be expected in the near future unless a breakthrough in deposition of cubic boron nitride and diamond takes place. In the mean time improvement in formulating the optimal sequence and thickness of the three basic coatings - TiC, TiN and Al<sub>2</sub>O<sub>3</sub> will probably be the main course of progress in the field.

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TABLE I. - PROPERTIES OF MATERIALS

Material	Hardness Hvickers	Melting temperature, °C	Softening temperature, °C
WC	2400	2630	1091
TiC	3200	3140	1331
TiN	1950	2950	1242
TaC	1800	3880	1679
NbC	2400	3600	1547
Al <sub>2</sub> O <sub>3</sub>	3000	2000	795



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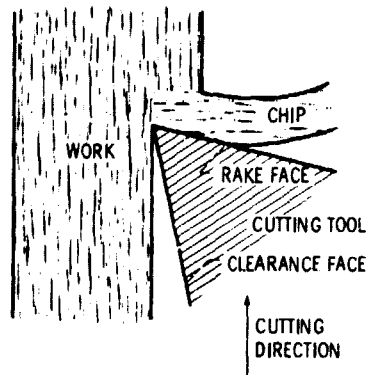


Figure 1. - Wear regions on a cutting tool.

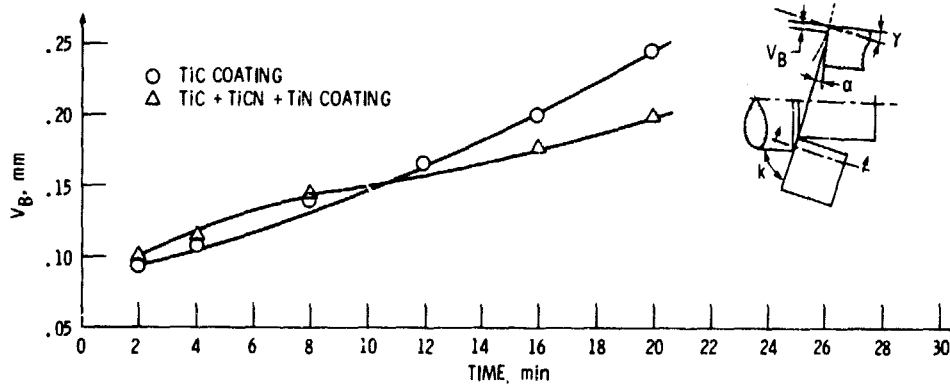


Figure 2. - Machining test results. Carbide grade, ISO P40 coated; indexable insert, TNMA 432; cutting speed, 160 m/min; depth of cut, 2.5 mm; feed, 0.36 mm/rev; material, AISI 1045.

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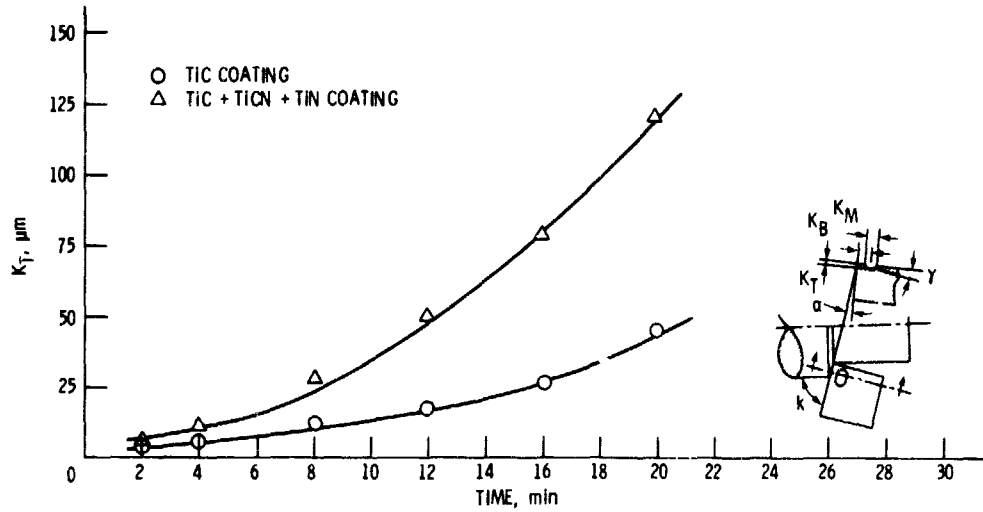


Figure 3. - Machining test results. Carbide grade, ISO P40 coated; indexable insert, TNMA 432; cutting speed, 160 m/min; depth of cut, 2.5 mm; feed, 0.36 mm/rev; material, AISI 1045.

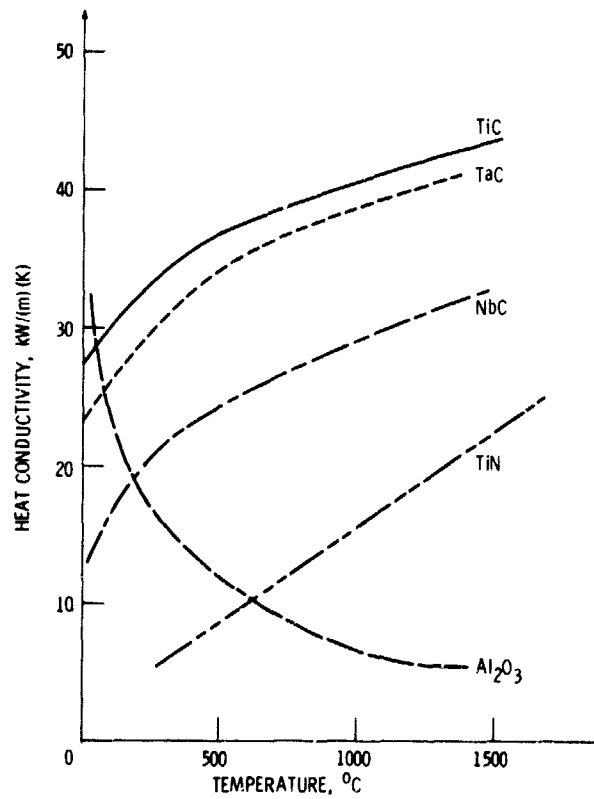


Figure 4. - Heat conduction of some wear-resistant materials.

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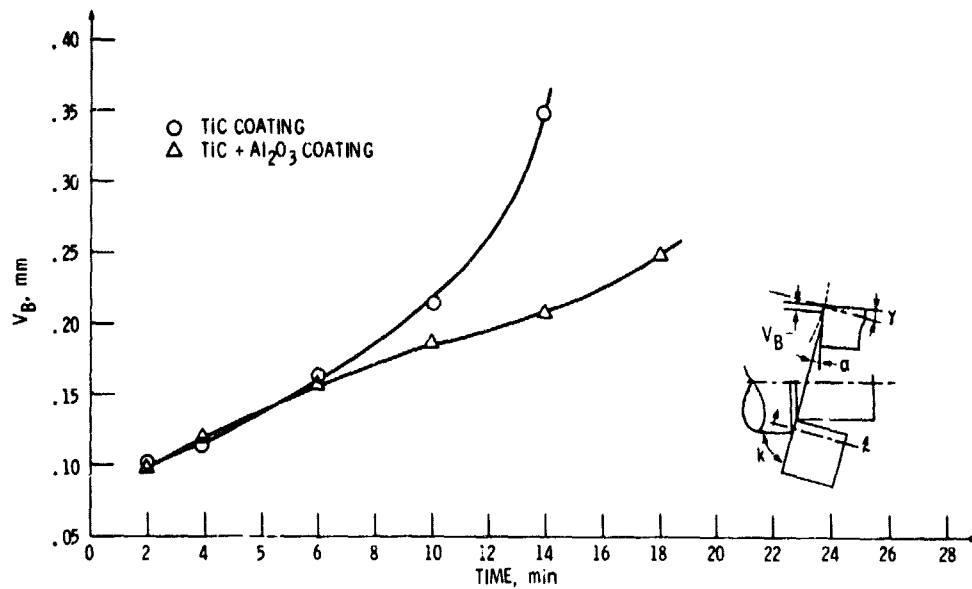


Figure 5. - Machining test results. Carbide grade, ISO M15 coated; indexable insert, TNMG 433; cutting speed, 240 m/min; depth of cut, 2.5 mm; feed, 0.25 mm/rev; material, AISI 1045.

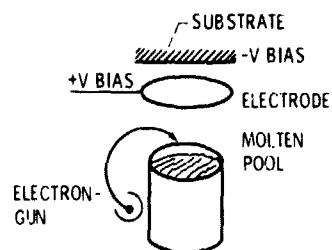


Figure 6. - Schematics of reactive ion plating.